Photonic heterostructure high contrast grating as a novel polarization control and light confinement system in HCG VCSEL

Gebski, M.; Dems, M.; Chen, J.; Qijie, W.; Dao Hua, Z.; Czyszanowski, T.

2014

Gebski, M., Dems, M., Chen, J., Qijie, W., Dao Hua, Z., & Czyszanowski, T. (2014). Photonic heterostructure High Contrast Grating as a novel polarization control and light confinement system in HCG VCSEL. SPIE Proceedings, 9134, 91341H-.

<https://hdl.handle.net/10356/103905>

<https://doi.org/10.1117/12.2052283>

© 2014 SPIE. This paper was published in SPIE Proceedings and is made available as an electronic reprint (preprint) with permission of SPIE. The paper can be found at the following official DOI: <http://dx.doi.org/10.1117/12.2052283>. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 18:24:49 SGT

Photonic heterostructure High Contrast Grating as a novel polarization control and light confinement system in HCG VCSEL

M. Gebiski^a, M. Dems^a, J. Chen^b, W. Qijie^{b,c}, Z. Dao Hua^b, T. Czyszanowski^a

^aLodz University of Technology, Institute of Physics, Photonics Group, Wólczańska 219, 90-924 Łódź, Poland;

^bDivision of Microelectronics, School of electrical and electronic engineering, Nanyang Technological University, 50 Nanyang Ave., 639798, Singapore;

^cDivision of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 637371, Singapore.

ABSTRACT

In this paper we present results of computer optical simulations of VCSEL with modified high refractive index contrast grating (HCG) as a top mirror. We consider the HCG of two different designs which determine the lateral aperture. Such HCG mirror provides selective guiding effect. We show that proper design of aperture of HCG results in almost sixfold increase in cavity Q-factor for zero order mode and a discrimination of higher order modes.

Keywords: High Contrast Grating, Vertical Cavity Surface Emitting Laser (VCSEL), computer simulations, photonic crystals

1. INTRODUCTION

The potential and actual applications in optical glass fiber based telecommunication have been the strongest driving force of development of Vertical Cavity Surface Emitting Lasers (VCSEL). The telecommunication VCSELs must fulfill several requirements: 1) Optical telecommunication standards restrict the transmitted wavelengths to 0.85 μm , 1.31 μm and 1.55 μm , 2) Due to dispersion relation, single mode operation of the device is crucial to obtain high bit rates at long distances, 3) Polarization control is highly desired, 4) Efficient coupling of the emitted light to the fiber is crucial.

Devices which fulfill those requirements „best seem to be the arsenide based VCSELs. The inherent feature of the VCSELs is the single longitudinal mode emission due to very short cavity. To enable laser emission in such design, high quality resonator is necessary to support large number of photon passes through active region. In order to create such resonator, distributed Bragg reflectors (DBR) are used. They consist of periodic, multi-layer, stack of semiconducting materials and provide reflectivity exceeding 99% for bandwidth as wide as 75 nm [1] enabling low threshold current and room temperature operation of VCSELs. Additionally to achieve single transversal mode emission several design schemes were proposed. Wet oxidation of AlGaAs layer of very high content of aluminum is the most commonly used. It creates the aperture for current and light due to very low electrical conductivity and low refractive index of outer, oxidized material in contrast with non oxidized inner material part. The drawback of the oxide apertures is their gradual degeneration by Galvanic process and diffusion of the oxidation [2] which leads to dramatic increase of threshold current and reduction of wall-plug efficiency of oxide-confined VCSELs.

Other methods, to mention only few of them; mesa etching, proton implantation are less efficient due to the mode discrimination. Buried tunnel junction provides record single mode emission power however to confine the light the thermal focusing effect is used which contributes to higher thresholds. Another interesting approach toward reliable single mode devices are photonic crystal (PhC) VCSELs [3]. Etched holes, periodically distributed over laser surface, introduce waveguide effect supported by the lateral Bragg reflections and leakage of high order modes which greatly contributes to low threshold and single mode emission. Important advantage of etched PhCs over oxidized AlAs layers is the versatility of the etch process which can be realized in any material system. The drawback is the large ratio of the depth to diameter of PhC holes which is technologically very challenging regarding present methods of etching.

The polarization control of the light emitted by VCSELs is still a challenging issue. The most efficient are shallow etching reliefs which drawback is stable polarization limited to small emitted powers. Recently discovered and preliminarily utilized High refractive index Contrast Gratings (HCGs) overcome many drawbacks of DBRs and lateral confinement schemes used earlier. The HCG, also called photonic crystal membrane, is composed of a single layer of periodically spaced stripes of high refractive index material interleaved with stripes of low refractive index material. Additionally, low refractive index layers are placed under and above the grating layer in order to enhance the confinement of the lateral mode (Fig 1.).

Fig. 1. Schematic view of high contrast grating where L - grating period, F - fill factor or duty cycle, h_{HCG} - HCG thickness. n_{low} - low refractive index medium, n_{high} - high refractive index medium.

To describe the properties of HCG it is necessary to define its basic geometrical parameters (Fig. 1) The HCG period L is defined as distance between exactly the same region in periodic structure of HCG, fill factor F is defined as the ratio of high refractive index stripe width to period and HCG thickness h_{HCG} is the width of the stripes. By proper adjustment of the period, fill factor and HCG thickness one can achieve the reflectivity exceeding 99% and a bandwidth as wide as 150 nm [5]. On the other hand, different HCG designs provide nearly 100% of transparency. In general, optimization of HCG parameters enables control of the reflectivity, bandwidth and spectral characteristic of an HCG mirror. Due to inherent symmetry in one in plane direction and periodicity in the other, HCG is characterized by very large polarization discrimination of light [6] which can also be controlled by adjusting HCG thickness, period and fill factor. Additionally, the HCG is scalable with the wavelength [4].

The extraordinary features of HCG occur for wavelengths which are comparable to the size of a HCG thickness and period. Mechanism of high reflectivity in these structures involves interaction between light diffracted and reflected from structure's interfaces. HCG periodicity determine discrete set of in plane HCG Bloch modes which can be excited by incident light. In general, at least one mode exist, independently from the HCG parameters – longitudinal 0th order mode which does not experience the diffraction. However, if the period and fill factor of a HCG are chosen in such a way that only one lateral HCG Bloch mode is excited (1st order mode), it interacts with 0th order mode at the HCG interfaces. Finally, if the proper HCG thickness is chosen, the phase shift between excited 0th order and 1st order Bloch modes leads to destructive interaction at the output plane of an HCG and exponential decay of the 0th order mode outside the HCG. Since exponentially decaying mode does not transport energy, no energy leaks from the resonator. In such case, the structure is characterized by extremely high reflectivity. However, if HCG thickness is changed in such a way that constructive interference appear for 0th and 1st order Bloch modes, the result is large transparency [4].

Mechanism described above requires the HCG to operate in so called dual mode regime [4] in order to obtain extremely high or low reflectivity. This regime can be described by the range of wavelengths (or ranges of an HCG period and fill factor) for which only 0th and 1st order Bloch modes exist. For shorter wavelengths (or bigger HCGs) more diffraction modes exist in the HCG. Their interaction ca not be fully controlled by adjustment of HCG parameters what results in non zero interference between them at the HCG interface. This regime is called diffraction regime and no extremely high or low reflectivity occurs. On the other hand, for longer wavelengths (or smaller HCGs) no higher diffraction orders appear. No interaction at the interfaces occur, hence it is impossible to obtain extremely high or low reflectivity either. This regime is called deep sub-wavelength regime. Light interacts with HCG like it was averaged refractive index layer rather than periodic structure and for that reason reflection mechanism resembles reflection of light from uniform material there.

2. COMPUTATIONAL MODEL

The core of our optical module consists of implementation of Plane-Wave Reflection Transformation method (PWRT) which is a modification of Plane-Wave Admittance Method (PWAM) [7]. In general, the PWRT method changes the problem of solving the set differential equations into the problem of finding eigenvalues of a matrix. It solves Maxwell equations in a frequency domain by using a plane-wave expansion within each layer and computes an analytical solution in the perpendicular direction. Such approach is possible due to transformation of the electromagnetic (EM) field to the diagonal coordinates. In particular, the Maxwell equations are first transformed into second-order matrix equations of the form

$$\frac{\partial^2 \vec{E}}{\partial z^2} = -\mathbf{P}_H \mathbf{P}_E \vec{E} \frac{\partial^2 \vec{H}}{\partial z^2} == -\mathbf{P}_H \mathbf{P}_E \vec{H} \quad (1)$$

where $\vec{E}$ and $\vec{H}$ are super-vectors containing Fourier coefficients of the components of the electric and magnetic field functions defined over the computational domain. Matrices $\mathbf{P}_E$ and $\mathbf{P}_H$ are computed by applying lateral differential operators present in Maxwell equations on a set of basis plane-wave functions. Eqs. (2) can be transformed into a set of decoupled equations, which can be solved analytically:

$$\frac{\partial^2 \tilde{E}}{\partial z^2} = -\Gamma^2 \tilde{E} \frac{\partial^2 \tilde{H}}{\partial z^2} == -\Gamma^2 \tilde{H} \quad (2)$$

where Γ is a diagonal matrix of propagation coefficients and super-vectors $\tilde{E}$ and $\tilde{H}$ contain the amplitudes of the corresponding modes propagating in the z -direction. As values of Γ can be real, imaginary, or complex, both the propagating and attenuating modes are considered. In the PWAM, the fields are matched using the admittance transfer technique and the eigenmode is found by searching for a complex frequency that yields a non-zero EM field distribution. On the other hand, the PWRT uses the concept of iteratively determined reflection matrix $\mathbf{R}$, which is defined in each layer as a relation between forward and backward propagating field ($\tilde{F}$ and $\tilde{B}$, respectively):

$$\tilde{B} = -\mathbf{R} \tilde{F} \quad (3)$$

This matrix can be directly used for computation of the reflection coefficient of a mirror or for determination of eigenmodes in VCSEL cavity. For the latter purpose it is sufficient to require that at both bottom and top edges of the laser structure there is no incident field and use the same root-finding algorithm as in classical PWAM. However, there is no need to use vertical absorbing boundary conditions, as both the top-most and the bottom-most layers can be considered as having infinite thicknesses. The PWRT is very computationally effective and capable of finding eigenmodes of any planar photonic structure, and any composition of those.

3. SIMULATION PARAMETERS

Simulated structure consisted of 35 pairs of GaAs/AlAs bottom DBRs deposited on GaAs substrate, a GaAs resonator composed of active region sandwiched between lower and upper GaAs spacer and a top HCG mirror (Fig. 2.). Thicknesses and refractive indices of the layers were summarized in Table 1.

Fig. 2. Schematics of the VCSEL structure (left) and an HCG together with coordinate system (right), where L is the the HCG period, $F \cdot L$ is the width of the HCG stripes, h_{HCG} is the thickness of the HCG stripes, h_{clad} is the thickness of the cladding.

Table 1. Layer thicknesses and refractive indices of a 980 nm HCG VCSEL..

Layer	Refractive index	Layer thickness [μm]
Air	1	∞
HCG stripes	3.52	0.106
HCG cladding	1.55	0.417
Upper VCSEL Spacer	3.52	0.1336
Active region	3.7	0.01
Lower VCSEL Spacer	3.52	0.1336
35 DBR pairs	2.95	0.0830
	3.52	0.0696
Substrate	3.52	∞

4. RESULTS

Fig. 3 shows that a uniform HCG top mirror, shaped in a square $11.68 \mu\text{m} \times 11.68 \mu\text{m}$ (20 HCG stripes characterized by period $L = 0.584 \mu\text{m}$ and fill factor $F = 0.4$) provides optical confinement for zero order mode and barely any first order mode discrimination.

Fig. 3. Diagram of a uniform HCG mirror (top view).

In order to prevent higher order lateral modes to emerge we simulated VCSEL with HCG heterostructure top mirror. In this structure, both period and fill factor are modified along the lateral direction of periodicity. With the change of fill factor and/or period of the HCG, destructive interference between 0th and 1st order modes vanishes, hence structure becomes anti-guiding. If the central HCG region is kept unchanged (guiding) while outer HCG regions fill factor and/or period change (from guiding to anti-guiding), photonic well is formed in the central region, while photonic barriers are formed in the outer region (Fig. 4). Photonic heterostructure prevents the side leakage of modes excited inside the HCG what in result squeezes first order mode to the guiding region and introduces anti-guiding region for higher order modes in the same way the oxide aperture does. Sciancalepore in [8] shows that in case of heterostructure composed of Si HCG stripes burried in SiO₂ in which period is abruptly changed, first order lateral mode confinement and increased modal discrimination occur.

Fig. 4. Diagram of a heterostructure HCG mirror (top view).

In our research we simulated VCSEL structures with heterostructure HCG top mirror characterized by fill factor of the aperture $F_{\text{aperture}} = 0.4$ and fill factor of the barriers varying from $F_{\text{barrier}} = 0.25$ up to $F_{\text{barrier}} = 0.50$ with period and thicknesses of the HCG layer and cladding layer unvaried and equal respectively $L = 0.584 \mu\text{m}$, $h_{\text{HCG}} = 0.106 \mu\text{m}$ and $h_{\text{cladd}} = 0.417 \mu\text{m}$. Obtained field intensity profiles are strongly influenced by the change of fill factor of the barriers (Fig. 5, 6). Strong side leakage of the modes is clearly visible in the Fig. 5a, 6a, 6c and 6e which corresponds to uniform HCG mirror. For $F_{\text{barrier}} = 0.28$ leakage is greatly decreased for zero order mode (Fig. 5b) as well as for higher order modes (Fig. 6b, 6d and 6f).

Fig. 5. Top view of zero order mode field intensities in the active region for $F_{\text{barrier}} = 0.40$ (a) and $F_{\text{barrier}} = 0.28$ (b).

Fig. 6. Top view of higher order modes fields intensities in the active region for $F_{\text{barrier}} = 0.40$ (a, c, e) and $F_{\text{barrier}} = 0.28$ (b, d, f).

Fig. 7 illustrate simulation results of heterostructure HCG VCSEL structures with different fill factor of barriers. It shows that for $F_{\text{barrier}} = 0.28$ Q factor of the cavity for the zero order mode is increased almost sixfold and small, first order mode discrimination occur. Observed effects are the result of suppressed side leakage of the mode which is a consequence of incorporation of barriers.

Fig. 7. Q factor vs. fill factor of barriers for zero order mode (diamonds) and higher order modes (circles, squares and triangles).

5. CONCLUSIONS

Using a three dimensional, fully vectorial, optical model we analyzed VCSEL with an HCG top mirror. Comparing uniform and heterostructure HCG mirrors we found the optimal design, characterized by fill factor of the barriers $F_{\text{barrier}} = 0.28$ which provides the best lateral mode confinement correlated with the highest cavity Q factor and small higher order modes discrimination.

REFERENCES

- [1] M. Amann, "Tuning triumph", *Nature Photonics*, Vol. 2, pp. 134-135, 2008.
- [2] A.R. Weidberg, "A study of the causes of VCSEL failure under humidity", VCSEL Day, Lausanne, 2013.
- [3] Dae-Sung Song, Se-Heon Kim, Hong-Gyu Park, Chang-Kyu Kim, and Yong-Hee Lee, "Single-fundamental-mode photonic-crystal vertical-cavity surface-emitting lasers", *Applied Physics Letters*, Vol. 80, No. 21, pp. 3901-3903, 2002.
- [4] C. J. Chang-Hasnain and W. Yang, "High-contrast gratings for integrated optoelectronics", *Advances in Optics and Photonics*, 4, 379-440, 2012.
- [5] S. Boutami, B. Ben Bakir, J.-L. Leclercq, and P. Viktorovitch, "Compact 1.55 μm room-temperature optically pumped VCSEL using photonic crystal mirror," *Electron. Lett.*, vol. 43, pp. 282-283, 2007.
- [6] M. Gebiski, M. Dems, J. Chen, W. Qijie, Z. Dao Hua and T. Czystanowski, "The Influence of Imperfections and Absorption on the Performance of a GaAs/AlOx High-Contrast Grating for Monolithic Integration With 980 nm GaAs-Based VCSELs", *Journal of Lightwave Technology* 31(23), 3853-3858 (2014),
- [7] M. Dems, R. Kotynski, and K. Panajotov, "PlaneWave Admittance Method — a novel approach for determining the electromagnetic modes in photonic structures" *Opt. Express*. 13, 3196-3207 (2005),
- [8] C. Sciancalepore, B. Ben Bakir, X. Letartre, J. M. Fedeli, N. Olivier, D. Bordel, C. Seassal, P. Rojo-Romeo, P. Regreny, and P. Viktorovitch, "Quasi-3D Light Confinement in Double Photonic Crystal Reflectors VCSELs for CMOS-Compatible Integration", *Journal of Lightwave Technology*, Vol. 29, No.13, 2011.